CHAPTER 8

Vehicle of Discovery

The Cassini Orbiter, with its scientific instruments, is an amazing "tool" for making remote observations. However, much work has to be done to get the spacecraft to its destination, and that is the story of mission design and execution, covered in the previous chapter, and of mission operations, covered in Chapter 10. In this chapter, we will examine the structure and design of the Cassini spacecraft, including onboard computers, radio receivers and transmitters, data storage facilities, power supplies and other items to support data collection by the science payload. The instruments themselves, on the Orbiter and within the Huygens Probe, are covered in Chapter 9.

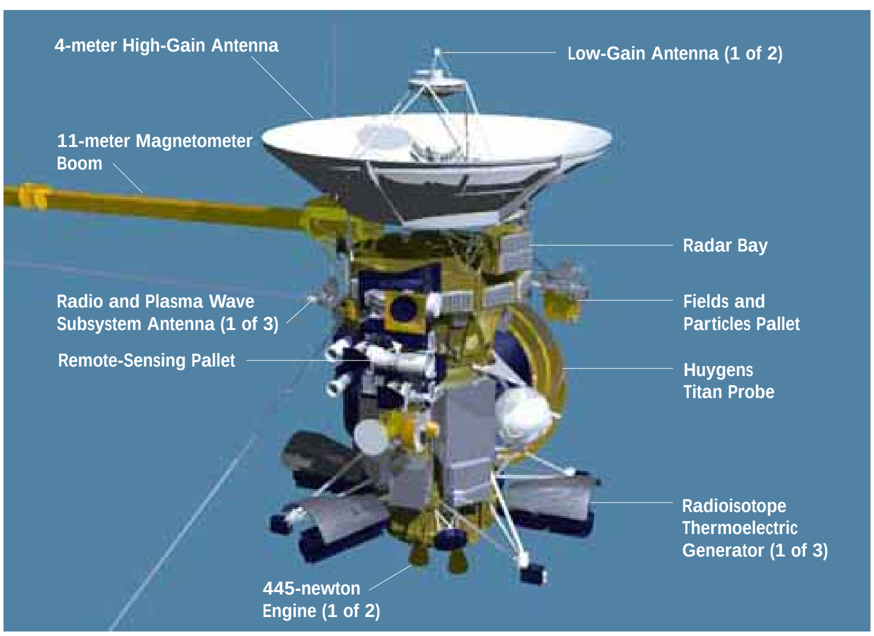
Orbiter Design

The functions of the Cassini Orbiter are to carry the Huygens Probe and the onboard science instruments to the Saturn system, serve as the platform from which the Probe is launched and science observations are made and store information and relay it back to Earth.

The design of the Orbiter was driven by a number of requirements and challenges that make Cassini–Huygens different from most other missions to the planets. Among these are the large distance from Saturn to the Sun and Earth, the length of the mission, the complexity and volume of the science observations and the spacecraft's path to Saturn. That path includes four "gravity assists" from planets along the way to Saturn.

General Configuration. The main body of the Orbiter is a stack of four main parts: the high-gain antenna (provided by the Italian space agency), the upper equipment module, the propulsion module and the lower equipment module. Attached to this stack are the remote-sensing pallet and the fields and particles pallet, both with their science instruments, and the Huygens Probe system (provided by the European Space Agency). The overall height of the assembled spacecraft is 6.8 meters, making Cassini–Huygens the largest planetary spacecraft ever launched.

The Huygens Probe contains instruments for six investigations. The Orbiter carries instrumentation for 12 investigations. Four science instrument packages are mounted on the remote-sensing pallet; three more are mounted on the fields and particles pallet. Two are associated with the high-gain antenna (HGA). The magnetometer is mounted on its own 11-meter boom. The remaining instruments are mounted directly on the upper equipment module.



This illustration shows the main design features of the Cassini spacecraft, including the Huygens Titan Probe.

Power Source. Because of Saturn's distance from the Sun, solar panels of any reasonable size cannot provide sufficient power for the spacecraft. To generate enough power, solar arrays would have to be the size of a couple of tennis courts and would be far too heavy to launch.

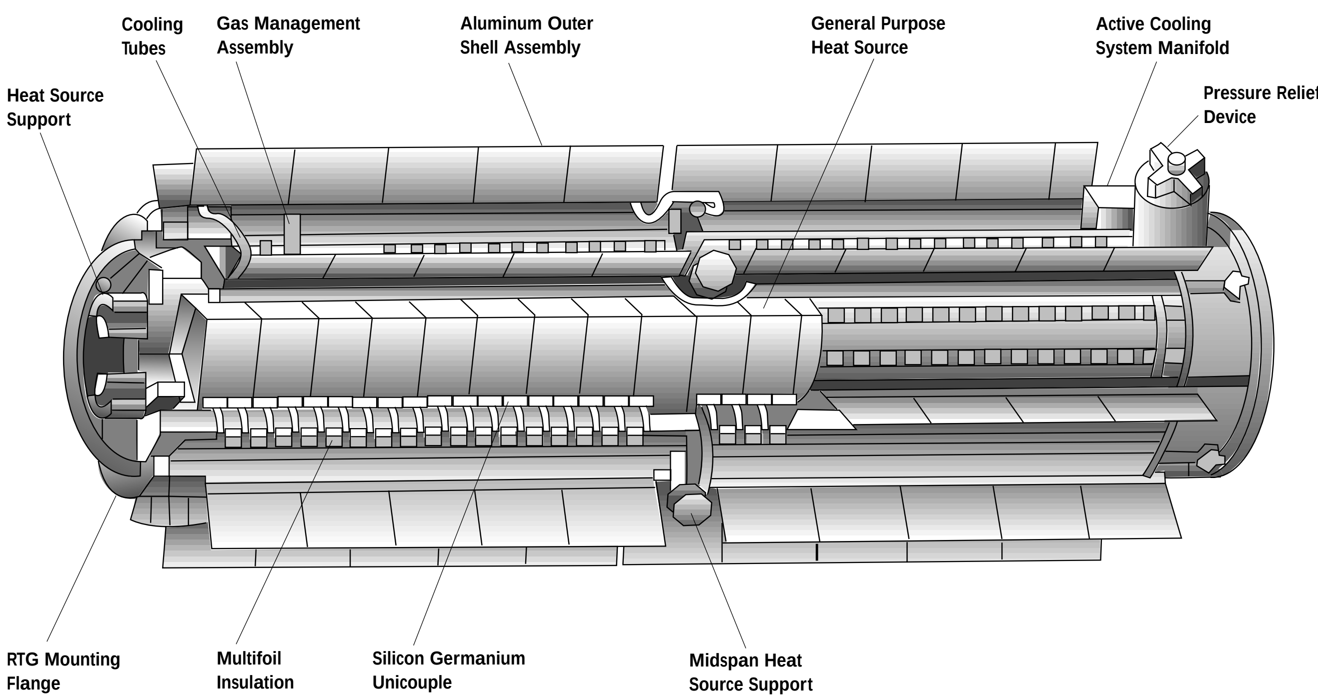
The Cassini Orbiter will get its power from three radioisotope thermoelectric generators, or RTGs, which use heat from the natural decay of plutonium to generate direct current electricity. These RTGs are of the same design as those already on the Galileo and Ulysses spacecraft and have the ability to operate many years in space. At the end of the 11-year Cassini–Huygens mission, they will still be capable of producing 630 watts of power! The RTGs are mounted on the lower equipment module and are among the last pieces of equipment to be attached to the spacecraft prior to launch.

Fault Protection. The distance of Saturn from Earth is especially important, because it affects communication with the spacecraft. When Cassini is at Saturn, it will be between 8.2 and 10.2 astronomical units (AU) from Earth (one AU is the distance from Earth to the Sun, or 150 million kilometers). Because of this, it will take 68–84 minutes for signals to travel from Earth to the spacecraft, or vice versa.

In practical terms, this means that mission operations engineers on the ground cannot give the spacecraft "real-time" instructions, either for day-to-day operations or in case of unexpected events on the spacecraft. By the time ground personnel become aware of a problem and respond, nearly three hours will have passed. Onboard fault protection is therefore essential to the success of the spacecraft. The Cassini–Huygens spacecraft system fault protection is designed to ensure that the spacecraft can take care of itself in the event of onboard problems long enough to permit ground personnel to study the problem and take appropriate action. In practical terms, this means that if a fault is detected that might pose a substantial risk to any part of the spacecraft, onboard computers automatically initiate appropriate "safing" actions. These may include terminating preprogrammed activities and establishing a safe, commandable and relatively inactive spacecraft state for up to several weeks without ground intervention.

Command and Data Subsystem. The primary responsibility for command, control (including the fault protection

Radioisotope thermoelectric generators (RTGs) have no moving parts and are highly reliable power sources.



discussed earlier) and data handling is performed by the actively redundant command and data subsystem (CDS). This computer executes sequences of stored commands, either as a part of a normal preplanned flight activity or as a part of fault-protection routines. The CDS also processes and issues real-time commands from Earth, controls and selects data modes and collects and formats science and engineering data for transmission to Earth.

The CDS electronics are located in Bay 8 of the 12-bay upper equipment module. Commands and data from the CDS to each instrument and data from the instruments are handled by bus interface units (BIUs), located in the electronics boxes of each instrument. The BIUs are also used by the CDS to control data flow and allowable power states for each instrument. The CDS can accommodate data collection from the instruments and engineering subsystems at a combined rate in excess of 430,000 bits per second while still carrying on its command and control functions!

Solid-State Recorders. The Cassini–Huygens spacecraft has been designed with a minimum of movable parts. In keeping with that design philosophy, data storage is accomplished by means of solid-state recorders rather than tape recorders. The two redundant solid-state recorders each had a storage capacity of two gigabits when they were built. Storage capacity is guaranteed to be at least 1.8 gigabits 15 years after

The Cassini–Huygens spacecraft, in launch configuration, in the Jet Propulsion Laboratory's High Bay.

launch. The solid-state recorders are located in Bay 9 of the upper equipment module.

The solid-state recorders have the ability to record and read out data simultaneously, record the same data simultaneously in two different locations on the same recorder and record simultaneously on both recorders. The recorders will be used to buffer essentially all of the collected data, permitting data transmission to Earth to occur at the highest available rates, rather than being restricted to instantaneous data collection rates. They can also be partitioned by command from the CDS. The recorders will be used to store backup versions of memory loads for almost all computers on the spacecraft and keep a running record of recent engineering activities to assist in the analysis of possible problems.

Attitude and Articulation Control. The attitude and articulation control subsystem (AACS) is primarily responsible for maintaining the orientation of

Cassini–Huygens in space. Specifically, the AACS is required to do the following tasks:

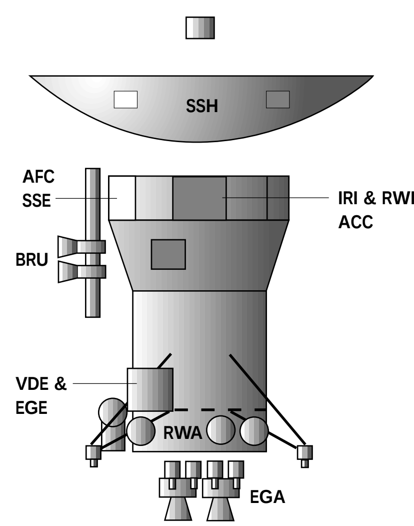
- Acquire a “fix” on the Sun following separation of the spacecraft from the launch vehicle.
- Point the antenna (either the high-gain or one of the two low-gain antennas) toward Earth when required.
- Point the high-gain antenna toward the Huygens Probe during its three-hour data collection period as it descends through the atmosphere and lands on Titan’s surface.
- Point the high-gain antenna at appropriate radar or radio science targets.
- Point the instruments on the remote-sensing pallet toward targets that are themselves in motion relative to the spacecraft.
- Stabilize the spacecraft for Probe release and gravity wave measurements.
- Turn the spacecraft at a constant rate around the axis of the high-gain antenna for fields and particles measurements during transmission of data to Earth or receipt of commands from Earth.
- Point one of the two redundant main propulsion engines in the desired direction during main engine burns.
- Perform trajectory correction maneuvers of smaller magnitude using the onboard thrusters.
- Provide sufficient data in the transmitted engineering data to support science data interpretation and mission operations.

The two redundant computers for the AACS are located in Bays 1 and 10 of the upper equipment module, but parts of the AACS are spread across the spacecraft. Redundant Sun sensors are mounted to the high-gain antenna. Redundant stellar reference units are mounted on the remote sensing platform. Three mutually perpendicular reaction wheels are mounted on the lower equipment module: A fourth reaction wheel, mounted on the upper equipment module, is a backup that can be rotated to be parallel to any one of the three other reaction wheels. Redundant inertial reference units, consisting of four hemispherical resonator gyroscopes each, are mounted to the upper equipment module. The main engine actuators and electronics are mounted near the bottom of the propulsion module. An accelerometer, used to measure changes in the spacecraft’s velocity, shares Bay 12 of the upper equipment module with the imaging science electronics.

A sophisticated pointing system known as inertial vector propagation is programmed into the AACS computers. It keeps track of spacecraft orientation, the direction and distance of the Sun, Earth, Saturn and other possible remote-sensing targets in the Saturn system and the spacecraft-relative pointing directions of all the science instruments — and thereby points any specified instrument at its selected target. The AACS uses the stellar reference unit to determine the orientation of the spacecraft by comparing stars seen in its 15-degree field of view to a list of more than 3000 stars stored in memory.

Propulsion Module Subsystem. The largest and most massive subsystem on the spacecraft is the propulsion module subsystem (PMS). It consists of a bipropellant element for trajectory and orbit changes and a hydrazine element for attitude control, small maneuvers and reaction wheel desaturation (“unloading”).

The bipropellant components are monomethyl hydrazine (fuel) and nitrogen tetroxide (oxidizer), and are identical and stacked in tandem inside the cylindrical core structure, with the fuel closer to the spacecraft high-gain antenna. The fuel tank is loaded with 1130 kilograms of monomethyl hydrazine; the oxidizer tank contains 1870 kilograms of nitrogen tetroxide. Their combined mass at launch, 3000 kilograms, constitutes more than half the total mass

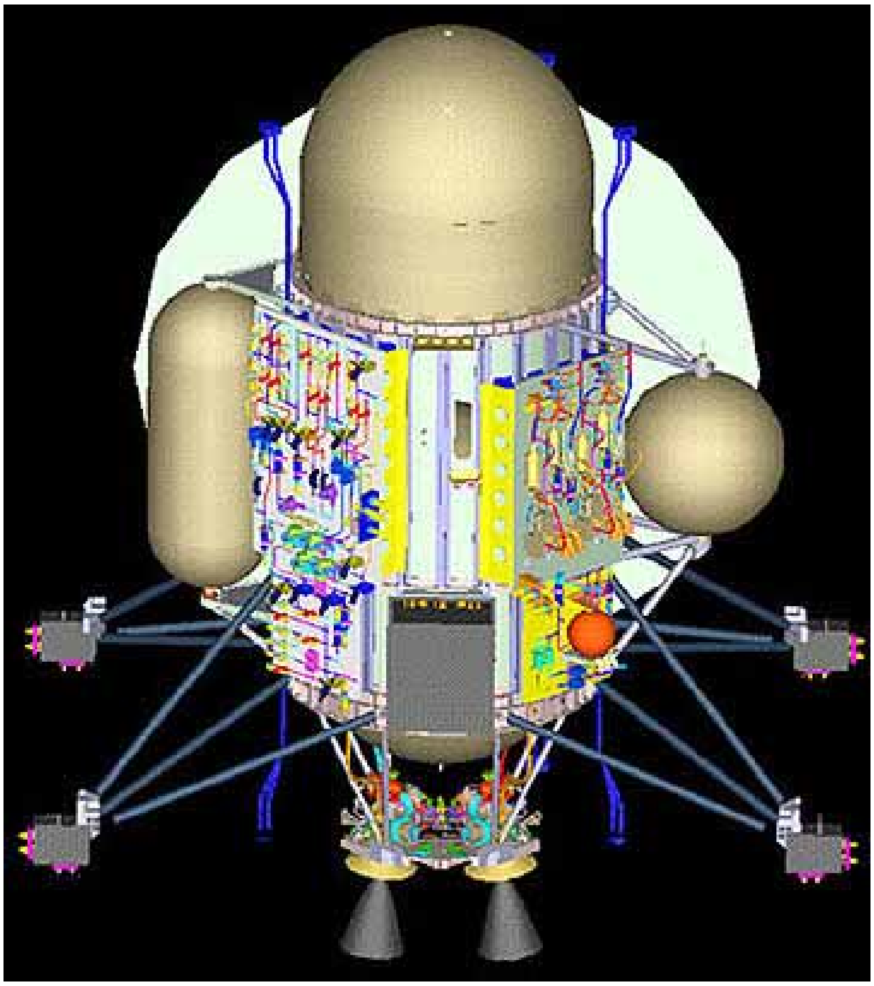


A diagram of the Cassini spacecraft showing elements of the propulsion module subsystem. (Acronyms are defined in Appendix B.)

of the spacecraft! Below the oxidizer tank are the redundant main engines, which can be articulated in each of two axes by the AACS. A heat shield protects the gimbal assembly and the spacecraft from engine heat.

The hydrazine tank is spherical and is mounted external to the PMS cylindrical structure. Hydrazine is used to power the small thrusters as commanded by the AACS. The 16 thrusters are located in clusters of four each on four struts extending outward from the bottom of the PMS. At launch, the tank holds 132 kilograms of hydrazine.

A larger cylindrical tank with rounded ends, also exterior to the PMS cylindrical structure but on the opposite side from the hydrazine tank, holds nine kilograms of helium. The helium tank supplies pressurant to expel propellants from the two bipropellant tanks and from the hydrazine tank.



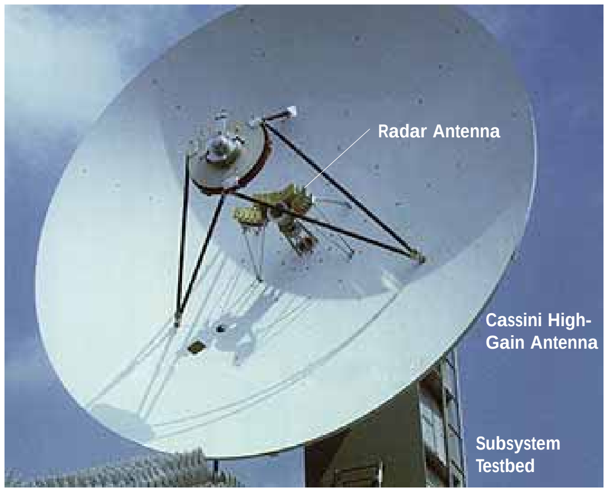
The propulsion module subsystem was tested in the Jet Propulsion Laboratory's Spacecraft Assembly Facility.

Telecommunications. The long-distance communications functions on the spacecraft are performed by the radio frequency subsystem (RFS) and the antenna subsystem. For telecommunications from the spacecraft to Earth, the RFS produces an X-band carrier at a frequency of 8.4 gigahertz, modulates it with data received from the CDS, amplifies the carrier and delivers the signal stream to the antenna subsystem for transmission. In the opposite direction, the RFS accepts X-band ground commands and data signals from the antenna subsystem at a frequency of 7.2 gigahertz, demodulates them and delivers the telemetry to the CDS for storage and / or execution. The RFS is contained in Bays 5 and 6 of the upper equipment module.

The antenna subsystem includes the four-meter-diameter high-gain antenna (HGA) and two low-gain antennas (LGA1 and LGA2). LGA1 is attached to the secondary reflector of the HGA and has a hemispherical field of view centered on the HGA field of view. LGA2 is mounted on the lower equipment module and has a hemispherical field of view centered on a direction approximately perpendicular to the HGA field of view. The two low-gain antennas are primarily used for communications during the first two and a half years after launch, when the HGA needs to be pointed at the Sun (to provide shade for most of the spacecraft subsystems) and cannot therefore be pointed at Earth. After the first two and a half years, the high-gain antenna is used almost exclusively for communications.

The spacecraft receives commands and data from Earth at a rate of 1000 bits per second during HGA operations. It transmits data to Earth at various rates, between 14,220

The Cassini high-gain antenna was provided by the Italian space agency.



and 165,900 bits per second. Lower rates of receipt and transmission apply for low-gain antenna operations. In general, during operations from Saturn, data will be recorded on the solid-state recorders for 15 hours each day, while the HGA is not pointed at Earth. Then, for nine hours each day (generally during Goldstone, California, tracking station coverage) the data from the solid-state recorders will be played back while data collection from the fields and particles investigations continues. In this fashion, approximately one gigabit of data can be returned each "low-activity" day via a 34-meter Deep Space Network antenna. Similarly, using a 70-meter antenna on "high-activity" days, approximately four gigabits of data can be returned in nine hours.

In addition to redundant X-band receivers and transmitters, the HGA also houses feeds for a K_a-band receiver, a K_a-band transmitter and an S-band transmitter, all for radio science. Feeds for K_u-band transmitters and receivers for radar science are also on the HGA, as is a feed for an S-band receiver for receipt of the Huygens Probe data.

Power and Pyrotechnics Subsystem. The radioisotope thermoelectric generators (discussed earlier) are a part of the power and pyrotechnics subsystem (PPS). The RTGs generate the power used by the spacecraft; the power conditioning equipment conditions and distributes that power to the rest of the spacecraft; the pyro switching unit provides redundant power conditioning and energy storage and, upon command, redundant power switching for firing electroexplosive or pyro devices.

The power conditioning equipment converts the RTG output to provide a regulated 30-volt direct current power bus. It also provides the capability to turn power on and off to the various spacecraft power users in response to commands from the CDS. If any power user experiences an overcurrent condition, the power conditioning equipment detects that condition; if the level of overcurrent exceeds a predetermined level, the power to that user is switched off.

The pyro switching unit controls the firing of pyro devices on 32 commandable circuits, most of which open or shut valves to control the pressures and flows within the propulsion module plumbing. The pyro devices are also used to:

- Separate the spacecraft from the launch vehicle after launch.
- Pull the pin that unlatches the spare reaction wheel articulation mechanism.
- Pull the pin that permits the Radio and Plasma Wave Science instrument's Langmuir probe to deploy.
- Jettison science instrument covers.
- Separate the Huygens Probe from the Cassini Orbiter.
- Jettison the articulated cover that protects the main engine nozzles from damage by high-velocity particles in space (in the event the cover sticks in a closed position).

Temperature Control Subsystem. The Cassini spacecraft has many electrical and mechanical units that are sensitive to changes in temperature. The function of the temperature control subsystem (TCS) is to keep these units within their specified temperature limits while they are on the spacecraft, during both prelaunch and postlaunch activities. The TCS monitors temperatures by means of electrical temperature sensors on all critical parts of the spacecraft. The TCS then controls the temperature of the various units by using one or more of the following techniques:

- Turning electrical heaters on or off to raise or lower temperatures.

- Opening or shutting thermal louvers (which resemble Venetian blinds) to cool or heat electronics in one of the bays of the upper equipment module.
- Using small radioisotope heater units to raise the temperatures of selected portions of the spacecraft that would otherwise cool to unacceptably low temperatures.
- Installing on the spacecraft thermal blankets (gold or black in color) to prevent heat from escaping to space.
- Installing thermal shields above the RTGs to keep them from radiating excessive heat to sensitive science instruments.
- Taking advantage of the orientation of the spacecraft to keep most of the spacecraft in the shadow of the high-gain antenna or the Huygens Probe.

From launch until Cassini–Huygens is well beyond the distance of Earth, the spacecraft is oriented to point the high-gain antenna at the Sun, thereby shading most of the rest of the spacecraft. Deviations from this orientation are permitted for a maximum of half an hour for each occurrence until the spacecraft reaches a distance of 2.7 AU (405 million kilometers) from the Sun. After that time, the heat input from the Sun will have diminished sufficiently to permit almost any spacecraft orientation.

Although they are not a part of the TCS responsibility, several instruments have radiator plates to cool their detectors. Even at the distance of Saturn from the Sun, spacecraft orientations that point those radiator plates in the same half of the sky as the Sun can severely degrade the data collected by some of the science instruments. In at least one case, it is even necessary to simultaneously avoid having Saturn illuminate the radiator plate(s).

New Technology. Whereas previous interplanetary spacecraft used onboard tape recorders, Cassini will pioneer a new solid-state data recorder with no moving parts. The recorder will be used in more than 20 other NASA and non-NASA missions.

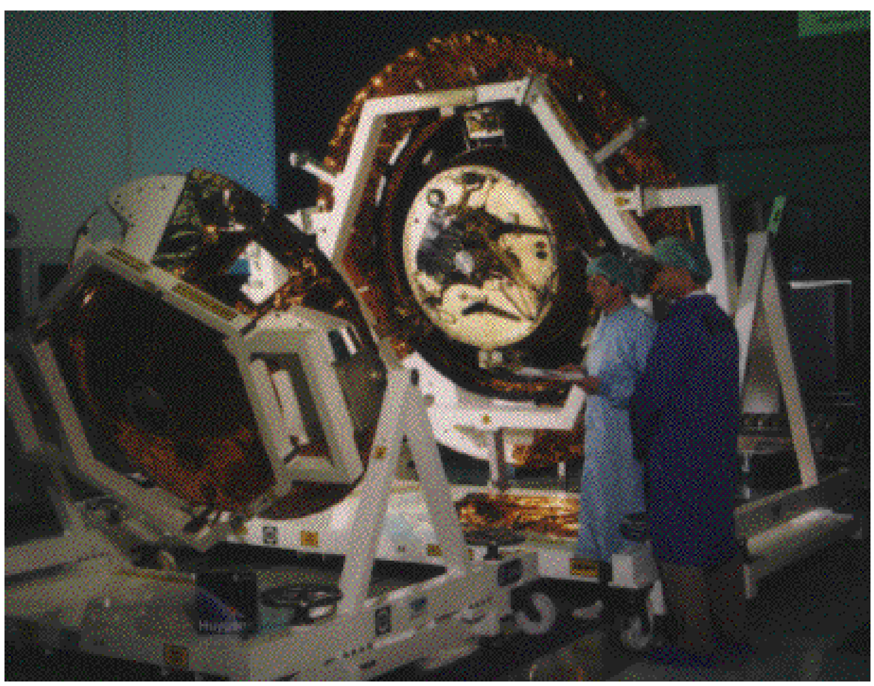
Similarly, the main onboard computer, which directs Orbiter operations, uses a novel design incorporating new families of electronic chips. Among them are very high speed integrated circuit (VHSIC) chips. The computer also contains powerful new application-specific integrated circuit (ASIC) parts, each replacing a hundred or more traditional chips.

Also on the Orbiter, the power system will benefit from an innovative solid-state power switch that will eliminate the rapid fluctuations or “transients” that can occur with conventional power switches. This will significantly extend component lifetime.

Past interplanetary spacecraft have used massive mechanical gyroscopes to provide inertial reference during periods when Sun and star references were unavailable. Cassini employs hemispherical resonator gyroscopes that have no moving parts. These devices utilize tiny “wine glasses” about the size of a dime that outperform their more massive counterparts both in accuracy and in expected lifetime.

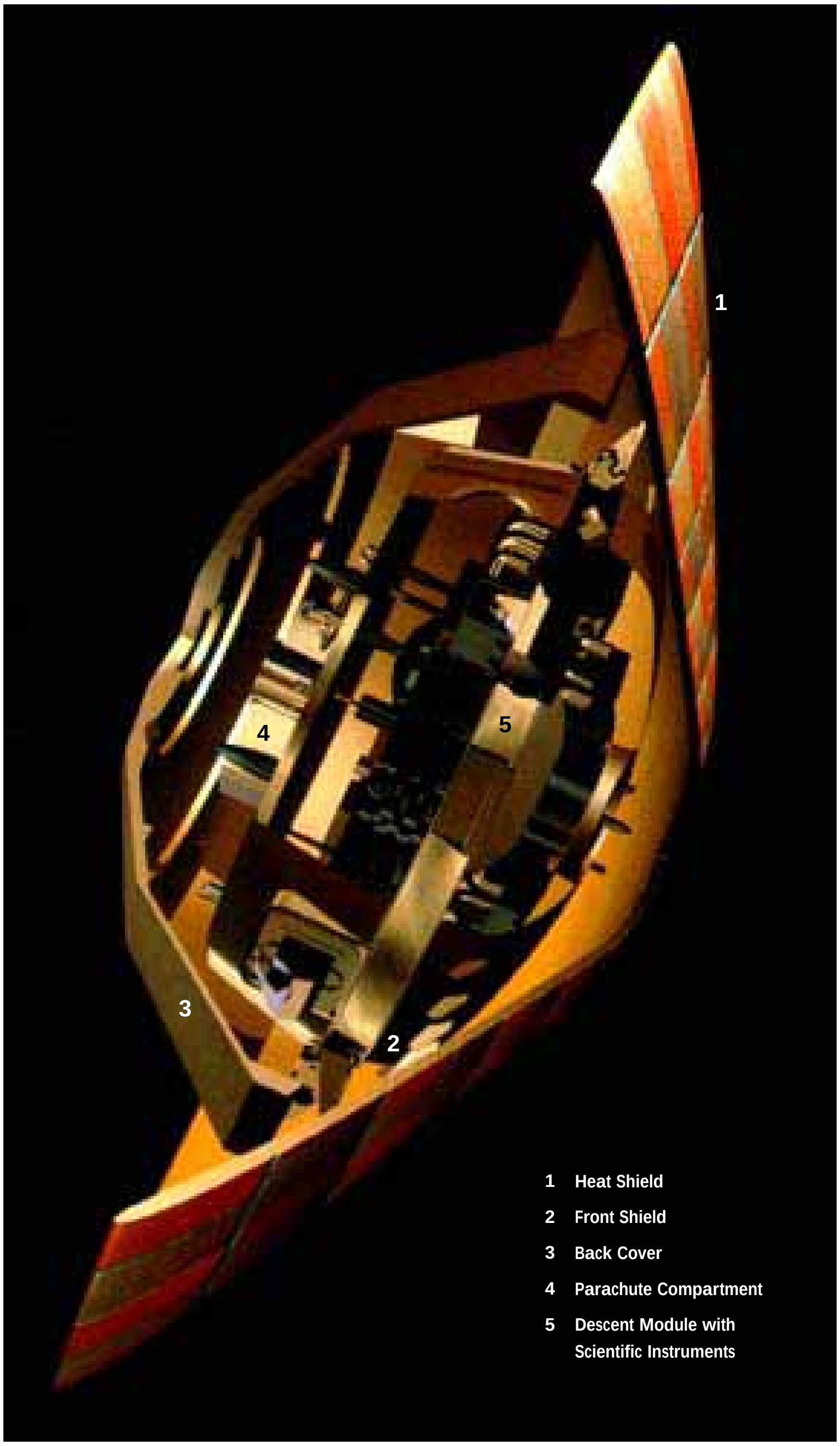
Huygens Probe Design

The Huygens Probe, supplied by the European Space Agency (ESA), will scrutinize the clouds, atmosphere and surface of Saturn’s moon Titan. It is designed to enter and brake in



Final European Space Agency inspection of the Huygens Probe prior to shipment to the United States for integration with the Cassini Orbiter.

The Huygens Probe carries six science investigations to study the clouds, atmosphere and surface of Titan. Three separate parachutes are carried in the Probe's parachute compartment. The heat shield, front shield and back cover are jettisoned before data collection begins.



Titan's atmosphere and parachute a fully instrumented robotic laboratory down to the surface. The Huygens Probe system consists of the Probe itself, which will descend to Titan, and the Probe support equipment, which will remain attached to the orbiting spacecraft.

The Probe will remain dormant throughout the 6.7-year interplanetary cruise, except for health checks every six months. These checkouts will follow preprogrammed descent scenario sequences as closely as possible, and the results will be relayed to Earth for examination by system and payload experts.

Prior to the Probe's separation from the Orbiter, a final health check will be performed. The "coast" timer will be loaded with the precise time necessary to turn on the Probe systems (15 minutes before the encounter with Titan's atmosphere), after which the Probe will separate from the Orbiter and coast to Titan for 22 days with no systems active except for its wake-up timer.

The Probe system is made up of a number of engineering subsystems, some distributed between the Probe and the Probe support equipment on the Orbiter. The Huygens payload consists of a complement of six science instrument packages.

Probe Support Equipment. The Probe support equipment includes the electronics necessary to track the Probe, recover the data gathered during its descent and process and deliver the data to the Orbiter, from which the data will be transmitted or "downlinked" to the ground.

The Probe engineering subsystems are the entry subsystem, the inner structure subsystem, the thermal control subsystem, the electrical power subsystem, the command and data management subsystem and the Probe data relay subsystem.

Entry Subsystem. The entry subsystem functions only during the release of the Probe from the Orbiter and its subsequent entry into the Titan atmosphere. It consists of three main elements: the spin–eject device that propels the Probe away from the Orbiter; a front shield covered with special thermal protection material that protects the Probe from the heat generated during atmospheric entry; and an aft cover, also covered with thermal protection material, to reflect away heat from the wake of the Probe during entry.

The Probe will be targeted for a high-latitude landing site on the "day" side of Titan and released from the Orbiter on November 6, 2004. The spin–eject device will impart a relative velocity of about 0.3 meter per second and a spin rate (for stabilization) of about seven revolutions per minute. The Probe's encounter with Titan is planned for November 27, when it will enter the atmosphere at a velocity of 6.1 kilometers per second. The entry phase will last about three minutes, during which the Probe's velocity will decrease to about 400 meters per second.

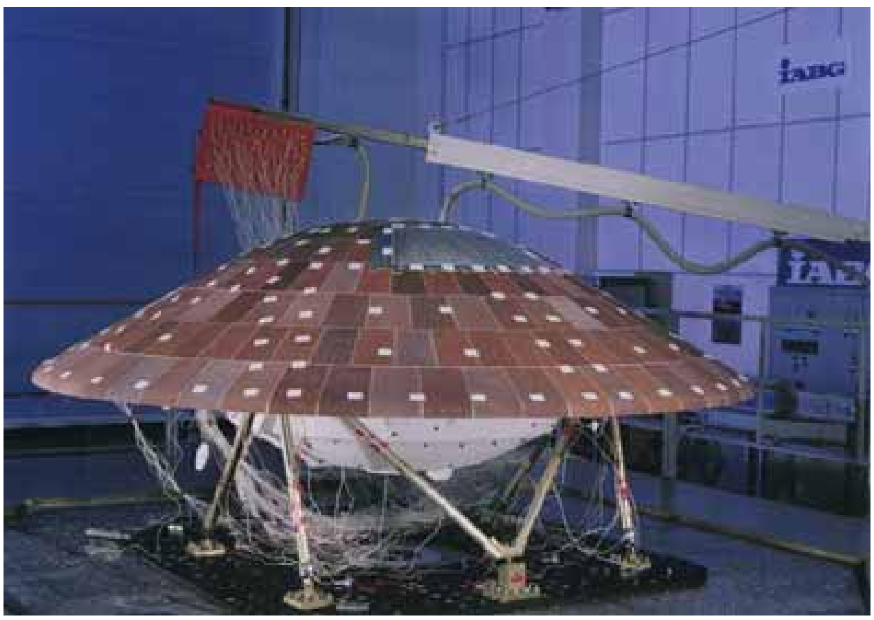
Three parachutes will be used during the Probe's descent. When the onboard accelerometers detect a speed of Mach 1.5 near the end of the deceleration phase, the two-meter-diameter pilot chute will deploy, pulling off the aft cover. This will be followed immediately by deployment of the 8.3-meter-diameter main parachute. About 30 seconds after deployment of the main chute, the Probe's velocity will have dropped from Mach 1.5 to Mach 0.6, and the front heat shield will be released.

At this point, scientific measurements can begin. About 15 minutes later, the main chute will be released and a smaller, three-meter drogue chute will permit the Probe to reach Titan's surface, about two and a half hours after data taking starts. The Probe will hit the surface at a velocity of about seven meters per second and is expected to survive the impact. The Probe will continue to transmit data for an additional 30–60 minutes.

Inner Structure Subsystem. The inner structure of the Probe consists of two aluminum honeycomb platforms and an aluminum shell. It is linked to the front heat shield and the aft cover by fiberglass struts and pyrotechnically operated release mechanisms. The central equipment platform carries, on both its upper and lower surfaces, the boxes containing the electrical subsystems and the science experiments. The upper platform carries the parachutes (when stowed) and the antennas for communication with the Orbiter.

Thermal Control Subsystem. At different times during the mission, the Probe will be subjected to extreme thermal environments requiring a variety of passive controls to maintain the required temperature conditions. For instance, during the two Venus flybys, the solar heat input will be high. The Probe will get some protection from the shadow of the high-gain antenna, and when the antenna is off Sun-point for maneuvers or communication, the Probe will be protected by multilayer insulation that will burn off during the later atmospheric entry.

The Probe will be at its coldest just after it separates from the Orbiter. To ensure that none of the equipment



AQ60 tiles, similar to those used on the Space Shuttle, will help to dissipate heat during the Huygens Probe's descent through Titan's atmosphere.

SPACECRAFT SUBSYSTEMS MASS AND POWER

Subsystem or Component	Mass, kilograms	Power, watts	Comments on Power Usage
Engineering Subsystems			
Structure Subsystem	272.6	0.0	
Radio Frequency Subsystem	45.7	80.1	During downlinking of data
Power and Pyrotechnics Subsystem	216.0	39.1	Shortly after launch
Command and Data Subsystem	29.1	52.6	With both strings operating
Attitude and Articulation Control Subsystem	150.5	115.3	During spindown of spacecraft
(Engine Gimbal Actuator)		31.0	During main engine burns
Cabling Subsystem	135.1	15.1	Maximum calculated power loss
Propulsion Module Subsystem (dry)*	495.9	97.7	During main engine burns
Temperature Control Subsystem	76.6	117.8	During bipropellant warmup
		6.0	Temperature fluctuation allowance
		2.0	Radiation and aging allowance
		20.0	Operating margin allowance
Mechanical Devices Subsystem	87.7	0.0	
Packaging Subsystem	73.2	0.0	
Solid-State Recorders	31.5	16.4	Both recorders reading and writing
Antenna Subsystem	113.9	0.0	
Orbiter Radioisotope Heater Subsystem	3.8	0.0	
Science Instrument Purge Subsystem	3.1	0.0	
System Assembly Hardware Subsystem	21.7	0.0	
Total Engineering Mass*	1756.6		
Science Instruments			
Radio Frequency Instrument Subsystem	14.4	82.3	Both S-band and K_a-band operating
Dual Technique Magnetometer	8.8	12.4	Both scalar and vector operations
Science Calibration Subsystem	2.2	44.0	In magnetometer calibration mode
Imaging Science (narrow-angle camera)	30.6	28.6	Active and operating
Imaging Science (wide-angle camera)	25.9	30.7	Active and operating
Visible and Infrared Mapping Spectrometer	37.1	24.6	In imaging mode
Radio and Plasma Wave Science	37.7	17.5	During wideband operations
Ion and Neutral Mass Spectrometer	10.3	26.6	Neutral Mass Spectrometer operating
Magnetospheric Imaging Instrument	29.0	23.4	High-power operations
Cosmic Dust Analyzer	16.8	19.3	Operating with articulation
Cassini Radar	43.3	108.4	Operating in imaging mode
Cassini Plasma Spectrometer	23.8	19.2	Operating with articulation
Ultraviolet Imaging Spectrograph	15.5	14.6	On in sleep state
Composite Infrared Spectrometer	43.0	43.3	Active and operating
Total Science Mass	338.2		
Huygens Probe (including Probe support)	350.0	249.8	During Probe checkouts
Launch Vehicle Adaptor Mass	136.0	0.0	
TOTALS*	2580.7	680.5	Power available at middle of tour

** Note that the masses given above do not include approximately 3141 kilograms of propellant and pressurant.*

falls below its storage temperature limits, the Probe will carry a number of radioisotope heater units that each generate one watt.

At described above under the entry subsystem, the front heat shield will protect the Probe during initial atmospheric entry. The front shield is covered with Space Shuttle–like tiles made of a material known as AQ60, developed in France. This material is essentially a low-density “mat” of silica fibers. The tile thickness of the front shield is calculated to ensure that the temperature of the structure will not exceed 150 degrees Celsius, below the melting temperature of lead. The rear side of the Probe will reach much lower temperatures, so a sprayed-on layer of “Prosial” silica foam material will be used on the rear shield. The overall mass of the thermal control subsystem will be more than 100 kilograms, or almost one-third of the entire Probe mass.

Electrical Power Subsystem. During Probe checkout activities, the Probe will obtain power from the Orbiter via the umbilical cable. After separation, the Orbiter will continue to supply power to the Probe support equipment, but power for the Probe itself will be provided by five lithium–sulphur dioxide batteries.

Much of the battery power will be used to power the timer for the 22 days of “coasting” to Titan. The higher current needed for Probe mission operations is only required for the science data collection period, three to three and a half hours. The electrical power subsystem is designed to survive the loss of one of its five batteries and still support a complete Probe mission.

The Cassini–Huygens mission: an international collaboration.

Command and Data Management. The command and data management subsystem provides monitoring and control of all Probe subsystem and science instrument activities. Specifically, this subsystem performs the following functions:

- Time the 22-day coast phase to Titan and switch the Probe on just prior to atmospheric entry.
- Control the activation of deployment mechanisms during the descent to Titan’s surface.
- Distribute telecommands to the engineering subsystems and science instruments.
- Distribute to the science instruments a descent data broadcast providing a timeline of conditions on which the instruments can base the scheduling of mode changes and other operations.
- Collect science and housekeeping data and forward the data to the Orbiter via the umbilical cable (before Probe separation) or via the Probe data relay subsystem (during descent).

Probe Data Relay Subsystem. The Probe data relay subsystem provides the one-way Probe-to-Orbiter communications link and includes equipment on both Probe and Orbiter. The elements that are part of the Probe support equipment on the Orbiter are the Probe system avionics and the radio frequency electronics, including an ultrastable oscillator and a low-noise amplifier.

The Probe carries two redundant S-band transmitters, each with its own antenna. The telemetry in one link is delayed by about four seconds with respect to the other link, to prevent data loss if there are brief transmission outages. Reacquisition of the Probe's signal by the Orbiter would normally occur within this interval.

Concluding Remarks

The design of the Cassini–Huygens spacecraft is the end result of extensive trade-off studies that considered cost, mass, reliability, durability, suitability and availability of hardware.

To forestall the possibility of mechanical failures, moving parts were eliminated from the spacecraft wherever feasible. Early designs that included articulating instrument scan platforms or turntables were discarded in favor of body-fixed instruments whose pointing will require rotation of the entire spacecraft.

Tape recorders were replaced with solid-state recorders. Mechanical gyroscopes were replaced with hemispherical resonator gyroscopes. An articulated Probe relay antenna was discarded in favor of using the high-gain antenna to capture the Probe's signal.

Spacecraft engineers, both those who designed and built the hardware and those who will operate the spacecraft, relied heavily on extensive experience to provide a spacecraft design that is more sophisticated, reliable and capable than any other spacecraft ever built for planetary exploration. Because of that care in design, the Cassini–Huygens spacecraft will be far easier to operate and will return more science data about its targets than any prior planetary mission!